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Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trends

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Abstract

During the last decade a significant progress has been reached in the investigation of the gravity field of the Earth. Besides static, also time variable geopotential models have been recently created. In this paper we investigate the impact of the recent time variable geopotential models on altimetry satellite orbits and such altimetry products based on these orbits, as global and regional mean sea level trends. We show that the modeling of time variable gravity improves the orbit solutions, at least for the GRACE period where time variable gravity is sufficiently accurately observed by this mission. Our analysis includes six geopotential models jointly developed by GFZ German Research Centre for Geosciences and Space Geodesy Research Group (CNES/GRGS) Toulouse: the stationary model EIGEN-GL04S, a stationary version of EIGEN-6S (EIGEN-6S_stat), a corrected version of EIGEN-6S and three enhanced versions of EIGEN-6S called EIGEN-6S2, EIGEN-6S2A and EIGEN-6S2B. By "stationary" we mean "containing periodic parameters such as annual and semi-annual variations, but no secular (drift) terms". We computed precise orbits for the radar altimetry satellites ERS-1, ERS-2, TOPEX/Poseidon, and Envisat over 20 years between 1991 and 2011. The orbit, single-mission and multi-mission altimetry crossover analyses show that the time variable models EIGEN-6S_corrected, EIGEN-6S2 and its two precursors EIGEN-6S2A/B perform notably better than the stationary models for the GRACE period from 2003 onwards. Thus, using EIGEN-6S2 and EIGEN-6S2A/B we have got 3.6% smaller root mean square fits of satellite laser ranging observations for Envisat, as when using EIGEN-GL04S. However, for the pre-GRACE period 1991 – 2003, the stationary geopotential models EIGEN-GL04S and EIGEN-6S_stat as well as EIGEN-6S2 having no drift terms for degree 3–50 at this time interval perform superior compared to EIGEN-6S_correct and EIGEN-6S2A/B which contain drifts for this period.

We found, that the time variable geopotential models have a low (0.1-0.2 mm/yr) impact on our results for the global mean sea level trend. However, we found strong East/West differences up to 3 mm/yr in the regional mean sea level trends when using orbits of all four satellites based on time variable and stationary geopotential models. We show that these differences are related to the relative drifts of the centers-of-origin between the orbit solutions based on the time variable and stationary geopotential models. From the results of our detailed study, we conclude that the final version of the time variable gravity field model EIGEN-6S2 performs best for the four satellites tested. This model provides the most reliable and mission-consistent sea level estimates for the whole time period from 1992 to 2010. This model is of maximum spherical harmonic degree and order 260 and contains time series for drifts as well as annual and semiannual variations of the spherical harmonic coefficients for degree 2–50.

Keywords: precise orbit determination, altimeter satellites, time variable geopotential models, mean sea level, Envisat, TOPEX/Poseidon

1. Introduction

Precise orbits of altimetry satellites are a prerequisite for various scientific investigations and applications such as investigations of global and regional mean sea level changes, altimetry mission cross-calibration, generation of mean sea surface height models, and others. Determination of precise orbits of artificial Earth satellites is a complex and challenging task. The accuracy of precise orbits of altimetry satellites depends on many factors, such as different tracking data, diverse models and algorithms, the reference frame implementation, various corrections, the applied parameterization, and some other effects. Since altimetry satellites are orbiting the Earth at altitudes between 700 and 1,400 km, the motion of these satellites is mainly affected by the following forces: gravitational attraction of the Earth, the Moon, the Sun, and the major planets of the Solar System, Earth tides, ocean tides, the gravitational attraction of the atmosphere, non-conservative forces due to atmospheric drag, albedo and infrared radiation of the Earth, and solar radiation pressure. During precise orbit determination (POD) the disturbing impact of unmodeled and mismodeled forces is usually mitigated respectively absorbed by empirical accelerations estimated by means of least square adjustment. The gravitational attraction of the Earth is the largest force acting

on satellites and probing of satellite orbits itself has been applied for the estimation of the detailed structure of the Earth’s gravity field since the launch of the first satellites more than fifty years ago.

During the past decades a significant progress has been reached in the investigation of the inhomogeneous Earth’s gravity field. Milestones in this context were set by the development of the GEM-T gravity field models (Lerch et al., 1992) and later by the generation of the first GRIM4 models. For example, the static geopotential model GRIM4-S1/C1 (Schwintzer et al., 1991) was developed using optical, laser and Doppler tracking data out of the time span 1964–1988 to totally 27 satellites at altitudes between 620 km (PEOLE) to 20,000 km (Etalon-1) and comprises spherical harmonic coefficients to degree and order 50 including a linear trend for the $C_{2,0}$ term.

A real improvement in the satellite-based gravity field determination was reached by the introduction of dedicated empirical accelerations into the satellite orbit determination. This was possible at that time due to denser tracking data of newer altimetry missions like TOPEX/Poseidon and some others. One important milestone in this context was the generation of the JGM gravity field series (Tapley et al., 1996), followed by the publication of the model GRIM4-S4/C4 (Schwintzer et al., 1997). Its subsequent geopotential model GRIM5-S1 (Biancale et al., 2000) is based on analyses of gravitational satellite orbit perturbations from 21 satellites at the altitudes between 400 km (GFZ-1) and 20,000 km (Etalon-1 and Etalon-2) and contains the spherical harmonic coefficients up to degree 99 together with the linear drifts for $C_{2,0}$, $C_{3,0}$ and $C_{4,0}$ coefficients. GRIM5-S1 features an approximated cumulated error of about 45 cm in terms of geoid height at degree 32 corresponding to 3 mGal in terms of gravity anomalies at $5^\circ \times 5^\circ$ spatial resolution.

A new era in the satellite-based gravity field determination started with the German geoscientific satellite ”CHALLENGING Mini-Satellite Payload” (CHAMP) launched on 15 July 2000 into nearly circular orbit with an initial altitude of about 454 km and an inclination of 87.3° . Only three months of onboard CHAMP Global Positioning System (GPS) satellite-to-satellite tracking data (GPS-SST) and accelerometer measurements, together with the GRIM5-S1 normal equations as well as LASER GEODynamics Satellite-1/2 (LAGEOS-1/2), Starlette and Stella laser tracking data, were sufficient to yield the first European Improved Gravity model of the Earth by New techniques (EIGEN) model EIGEN-1S (Reigber et al., 2002) which is of maximum degree 119. The cumulated error of this model at degree 36 is about twice smaller (about

20 cm in terms of geoid height) as for pre-CHAMP satellite-only geopotential models like GRIM5-S1. The subsequent geopotential EIGEN model EIGEN-2 (Reigber et al., 2003) was derived only from CHAMP data using six months of GPS-SST and accelerometer measurements. This model showed an additional significant improvement since it has an cumulated error of 10 cm corresponding to 0.5 mGal at degree 36 corresponding approximately to $5^\circ \times 5^\circ$ spatial resolution.

A further significant progress in the investigation of the Earth's gravity field has been reached with the twin satellite mission GRACE (Gravity Recovery and Climate Experiment, Tapley et al. (2004)) launched on 17 March 2002 into an almost circular orbit at an initial altitude of about 500 km and an inclination of 89.0° . Since then many gravity field models using GRACE data have been published by several teams.

Some of the first geopotential models derived from GRACE data were EIGEN-GRACE02S (Reigber et al., 2005) and GGM02S (Tapley et al., 2005). The EIGEN-GRACE02S model was computed from only 110 days of GRACE GPS-SST and K-Band range rate data. This model is complete to degree and order 150 and has an accuracy of about 1 mm at a resolution of 1,000 km half-wavelength, i.e. it is about one order of magnitude more accurate than CHAMP-derived geopotential models. GGM02S has basically the same accuracy. This model includes 14 months of GRACE data and is of maximum degree and order 160. GGM02S was accompanied by GGM02C (Tapley et al., 2005) which is of maximum degree and order 360 and was one of the first high resolution combined geopotential models including GRACE data. In 2008 the satellite-only geopotential model EIGEN-GL04S1 (up to degree and order 150) was created by using 30 months of GRACE and LAGEOS data (Förste et al., 2008b). At that time the new high-resolution combined geopotential model EIGEN-GL04C (Förste et al., 2008b) was obtained by combining surface gravity data sets with the EIGEN-GL04S1 data. EIGEN-GL04C is of maximum degree and order 360 and allows to resolve geoid and gravity anomalies at half-wavelength of 55 km with the mean accuracy of about 15 cm. In contrast to EGM96 (Earth Gravitational Model 1996, Lemoine et al. (1998)) new data sets for the oceans, the Arctic and North America were included in this model. The satellite-only geopotential model EIGEN-5S released in 2008 (Förste et al., 2008a) was again complete to degree and order 150, but compared to EIGEN-GL04S1 more GRACE (August 2002 – January 2007) and LAGEOS (January 2002 – December 2006) data were included to derive this model. The corresponding high-resolution

combined geopotential model EIGEN-5C (Förste et al., 2008a) is also up to degree and order 360 but was created by including new ground data sets for Australia and Europe.

A new generation of the Earth’s gravity field models has been derived from the first gravitational gradiometry satellite mission GOCE (Gravity field and Ocean Circulation Explorer, Floberghagen et al. (2011)) which was launched on 17 March 2009 into a sun synchronous and nearly circular orbit with an altitude of about 295 km and an inclination of 96.7° . European Space Agency’s (ESA) latest GOCE geopotential models are GO_CONS_GCF_2_TIM_R4 model based on the time-wise approach (Pail et al., 2011) and GO_CONS_GCF_2_DIR_R4 model from the direct approach (Bruinsma et al., 2013). Further models based on GOCE data combined with CHAMP, GRACE and other satellite data are GOCO01S, GOCO02S and GOCO03S (Pail et al., 2010) as well as EIGEN-6S and EIGEN-6C (Shako et al., 2014).

Besides the mentioned static mean Earth’s gravity field models, also time variable monthly (Luthcke et al., 2006) and 10-day gravity field models (Lemoine et al. (2007); Bruinsma et al. (2010)) were computed using GRACE data. However, these models are available only since the beginning of the GRACE mission 2002. To take into account time variable gravity before 2002, one can extrapolate the time variable terms of mean models like EIGEN-6S (see Section 3) before the GRACE period. Or one can use time series of low degree geopotential coefficients based on SLR (satellite laser ranging) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) observations to various satellites (e.g. Cheng et al. (2011), Zelensky et al. (2012)) for an approximate modeling of the temporal gravity variations. Another approach uses temporal variations of local point mass concentrations (mascons) which were computed from DORIS observations (Cerri et al., 2013). This method has been successfully demonstrated recently for the period 2002 – 2012.

Time variable Earth gravity field models have a strong impact on the orbit estimation for altimetry satellites and thereby on the computation of regional mean sea level trends using such orbits. In this context, Ollivier et al. (2012) point to significant East-West differences for the regional mean sea level (MSL) trends computed using Envisat (the Environmental Satellite) and Jason-1 orbits for the period 2002 – 2012 but based on two versions of geophysical data records (GDR) POD standards, namely GDR-C (Cerri et al., 2010) and GDR-D (OSTM/Jason-2 Products Handbook, 2011). Since these POD standards differ by the inclusion of drift terms in the geopotential

models, but also by the reference frame realizations –ITRF2005 (Altamimi et al., 2007) and ITRF2008 (Altamimi et al., 2011)– and other models, it is difficult to address the source of the observed East-West differences in the regional sea level trends.

In our study we investigate the impact of six recent geopotential models on precise orbits of altimetry satellites as well as on global and regional mean sea level trends based on these orbits. We perform our analysis for a longer time span (1991 – 2011) and, besides Envisat, include orbits of three other satellites (the European Remote Sensing Satellites ERS-1 and ERS-2 and Ocean TOPography Experiment (TOPEX)/Poseidon, Fu et al. (1994)). The first of the geopotential models used is EIGEN-GL04S (Lemoine et al., 2007) which is based on two years of GRACE and LAGEOS data and which was used as a background model to compute the GDR-C orbits for Jason-1/2 and Envisat (Cerri et al., 2010) and the REAPER orbits (Rudenko et al., 2012) of ERS-1 and ERS-2. This model containing no drift terms for the geopotential coefficients has been chosen as a benchmark in our study. The other models included in this study are five more recent geopotential models. These are the time variable model EIGEN-6S (Förste et al., 2012) which is complete to degree and order 240 and based on GRACE, GOCE and LAGEOS data, its stationary version EIGEN-6S_stat (at epoch 2000.0) containing no drift terms except for $C_{2,0}$ coefficient, the time variable model EIGEN-6S2 and its two preliminary versions (EIGEN-6S2A and EIGEN-6S2B). All six models include annual and semi-annual variations of the geopotential coefficients for degree and order 2–50. These six geopotential models were used for the computation of precise satellite orbits for Envisat for the measurement time span April 2002 to January 2011, TOPEX/Poseidon for September 1992 till October 2005, ERS-1 for August 1991 till July 1996, and ERS-2 for May 1995 till February 2006. We have used the geopotential models as they are without studying the influence of particular geopotential coefficients or dedicated annual and semi-annual variations. The total time interval over these four satellite missions is 1991 – 2011. This 20-year time span is of particular interest for oceanographic studies such as investigations of global and regional mean sea level changes, the generation of sea surface height models and so on. Improved gravity field models improve the orbits of the altimetry satellites, which should consequently enhance the quality of the altimetry products. Vice versa, improved altimetry products such as mean sea surface height models and gravity anomalies are very important contributions for the generation of high-resolution geopotential models computed from the combi-

nation of satellite, terrestrial and altimetry-derived gravity data (Flechtner et al., 2006).

In our study we investigate the impact of the geopotential models on the root mean square (RMS) fits of observations, on orbital arc overlaps in radial, cross-track and along-track directions as well as on RMS and mean of crossover differences. Our selected best gravity field model provides the smallest absolute values of these quantities (or most of them) as well as consistent results of the multi-mission crossover analysis for all tested satellites and gives relative center-of-origin shifts with respect to (w.r.t.) the reference missions without a significant drift for all satellite missions (Section 5.3). We also study the influence of the geopotential models on the global and regional mean sea level trends.

This paper is organized as follows. The main background models and input data used for the precise orbit determination are given in Section 2 except for the geopotential models which are described in detail in Section 3. The results of the impact of the geopotential models on the observation residuals, arc overlaps, RMS and mean of altimeter crossover differences are outlined in Section 4. The quality assessment of the orbit solutions computed using various geopotential models based on a multi-mission crossover analysis is provided in Section 5. The focus in this chapter lies on the consistency of the solutions for different altimeter missions. The impact on the global and regional mean sea level trends is shown in Section 6. Finally, the conclusions are drawn and an outlook is provided (Section 7).

2. The main models and input data used for precise orbit determination

The orbits of all four satellites are computed in the same terrestrial reference frame (ITRF2008, Altamimi et al. (2011)) by using the common models given in Tables 1–2. Most of these models are mainly based on the IERS Conventions (2010) and are updated compared to the studies in Rudenko et al. (2012). The orbits are computed using GFZ’s software tool EPOS-OC (Earth Parameter and Orbit System – Orbit Computation), for some general features of this software see (Zhu et al., 2004)). For the altimetry crossover computation and the altimetry analysis of the orbits the Altimeter Database and Processing System (ADS, Schöne et al. (2010)) has been used which was also developed by GFZ. For ERS-1 and ERS-2, SLR and single satellite altimeter crossover data (SXO) were used. Additionally, PRARE (Precise

Range And Range-rate Equipment) measurements were included for ERS-2. The Envisat and TOPEX/Poseidon orbits were computed using SLR and DORIS observations. Additionally, single satellite altimetry crossover data were used at 8% of Envisat orbital arcs having DORIS data gaps. For each satellite, six orbit versions (VER2 to VER7) are computed using exactly the same background models except of the mentioned six different geopotential models as described in Section 3. VER1 was a preliminary (screening) version for each satellite which is not included in this study. The precise orbits of ERS-1, ERS-2 and Envisat are computed as seven-day arcs and those of TOPEX/Poseidon are calculated as 12-day arcs. Adjacent arcs have a two-day overlap except such arcs which are separated by an orbital maneuver. We estimated the following parameters at each arc: satellite state vector (Keplerian elements or Cartesian coordinates), atmosphere drag coefficients (estimated 4–8 times a day for ERS-1, ERS-2 and Envisat and 4 times a day for TOPEX/Poseidon), once per revolution empirical cross-track and along-track accelerations (adjusted 1–2 times a day for ERS-1, ERS-2 and Envisat and once a day for TOPEX/Poseidon). Furthermore, radiation pressure mismodeling has been also mitigated by estimating suitable satellite empirical accelerations. The parameterization of the atmosphere drag coefficients and empirical accelerations depends on the solar and geomagnetic activity – parameterization with a twice shorter time step was used on the days of high activity as described by Rudenko et al. (2012) – amount of observations and orbit altitude. Additionally SLR range biases were estimated for some stations. A time tag correction for altimeter crossovers relative to the SLR tracking data was estimated at the arcs containing altimetry crossover data. In the same way as in Rudenko et al. (2012), PRARE station Cartesian coordinates, range and time biases of each PRARE station, troposphere refraction coefficients for each PRARE station and satellite pass are adjusted for the ERS-2 arcs containing PRARE data. Since Envisat and TOPEX/Poseidon orbits are computed using DORIS observations in addition to SLR, a DORIS time bias is estimated per arc, frequency offset and tropospheric refraction are estimated per DORIS station and satellite pass. We apply the following weights for the different observation types: 3.6 cm for SLR, 10.0 cm for PRARE range and 0.1 cm/s for PRARE range-rate, 0.06 cm/s for DORIS and 5.4 cm for altimeter crossover data. These weights were obtained in an iterative process to get a posteriori sigma of unit weight close to 1 for all observation types used.

3. Description of the geopotential models used

A summary on the geopotential models used in this study is given in Tables 3–4. They include the maximum degree and order of each model and the herein used truncation level of the geopotential expansion, indicate whether the model contains drifts and annual and semiannual variations for geopotential coefficients and how the coefficient $C_{2,0}$ is modeled. The tables also give the reference epoch (calendar date) and the applied version of the IERS Conventions. The values for the geocentric gravitational constant GM of $3.986004415 \times 10^{14} m^3 s^{-2}$ and for the Earth mean equatorial radius of 6,378,136.46 m are the same for each of the six models.

3.1. EIGEN-GL04S

The first of the geopotential models used is EIGEN-GL04S (Lemoine et al., 2007). This model comprises annual and semiannual variations for all degree 2–50 terms. It is available from http://grgs.obs-mip.fr/grace/variable-models-grace-lageos/mean_fields. Since this gravity field model was used to compute the GDR-C standards orbits (Cerri et al., 2010) for Jason-1/2 and Envisat and REAPER orbits (Rudenko et al., 2012) for ERS-1 and ERS-2, and since this model contains no drift terms for geopotential coefficients, it has been chosen as a benchmark.

3.2. EIGEN-6S

The satellite-only gravity field model EIGEN-6S (Förste et al., 2011) was constructed using the following satellite and terrestrial data:
– LAGEOS-1/2 SLR data and GRACE GPS SST and K-band range-rate data from January 2003 to June 2009 (6.5 years). The LAGEOS and GRACE data processing was performed within the GRGS RL02 GRACE processing (Bruinsma et al., 2010). The LAGEOS/GRACE normal equations were of maximum degree/order 130 and contain five time variable parameters for each spherical harmonic coefficient up to degree and order 50:

$$\begin{aligned} \bar{C}_{nm}(t) = & \bar{C}_{nm}^0 + \dot{\bar{C}}_{nm} \Delta t + \bar{C}_{nm}^{SINA} \sin(2\pi \Delta t) + \bar{C}_{nm}^{COA} \cos(2\pi \Delta t) + \\ & + \bar{C}_{nm}^{SINS} \sin(2 \cdot 2\pi \Delta t) + \bar{C}_{nm}^{COSS} \cos(2 \cdot 2\pi \Delta t) \end{aligned} \quad (1)$$

with $\Delta t = t - t_{2005.0}$, in years of 365.25 days, where $\dot{\bar{C}}_{nm}$ means a time derivative of $\bar{C}_{nm}$.

The C coefficients in Formula 1 correspond to the bias at reference date (superscript 0), drift (dot), sine and cosine annual terms (SINA,COSA) and sine and cosine semi-annual terms (SINS,COSS), respectively. A gravity field model including such time variable spherical harmonic coefficients represents the mean temporal variations of the Earth's gravity field very well, as can be noted from Figure 5 in (Bruinsma et al., 2010).

- GOCE satellite gravity gradient (SGG) data: 6.7 months of SGG data from November 2009 to June 2010. Individual normal equations of maximum degree/order 240 were computed for each diagonal component (Vxx, Vyy and Vzz, Vxz was not included) by means of the GOCE direct approach (Pail et al., 2011). During the generation of the observation equations a 100 to 8 second band-pass filter was applied for all three SGG components, which means the SGG signal is filtered-out below degree about 50.

- To overcome the instability in the satellite data due to the GOCE polar gap, the GOCE-SGG normal equation was stabilized by the Spherical Cap Regularization (Metzler and Pail, 2005) using a GFZ internal LAGEOS/GRACE gravity field model at the polar gaps.

EIGEN-6S is available for download at the International Centre for Global Earth Models (ICGEM) data base at GFZ (<http://icgem.gfz-potsdam.de/ICGEM>).

The model EIGEN-6S_correct is a modification of EIGEN-6S where a correction term $\Delta\bar{C}_{20}$ is added to $\bar{C}_{20}$ in order to better represent the long term modulation of $\bar{C}_{20}$, according to the following formula:

$$\Delta\bar{C}_{2,0}(t) = a1 \cdot \sin(2\pi \cdot \Delta t / 18.6129) + a2 \cdot \cos(2\pi \cdot \Delta t / 18.6129) \quad (2)$$

with $a1 = -9.01895 \times 10^{-12}$, $a2 = -3.47674 \times 10^{-11}$ and $\Delta t = t - t_{2005.0}$, in years of 365.25 days.

This correction was obtained by a regression based on the LAGEOS-1/2 and GRACE time series jointly with the mean and drift terms.

3.3. EIGEN-6S_stat

The model EIGEN-6S_stat is a stationary version of EIGEN-6S containing only a bias at reference epoch 2000.0 and annual and semi-annual coefficients. The bias at reference epoch 2000.0 is obtained using the bias at reference epoch 2005.0 and the drift terms of EIGEN-6S.

3.4. *EIGEN-6S2A*

The gravity field models EIGEN-6S2/A/B are a new GFZ/GRGS satellite-only model series from the combination of LAGEOS, GRACE and GOCE data. EIGEN-6S2A and EIGEN-6S2B are internal preliminary versions of the final model EIGEN-6S2.

EIGEN-6S2A is complete to degree/order 260 and can be seen as an update of EIGEN-6S as well as a time variable version of the fourth release of ESA's GOCE gravity field model from the GOCE direct approach (Bruinsma et al., 2013). EIGEN-6S2A has the following differences compared to EIGEN-6S:

- LAGEOS-1/2 data comprises 25 years of SLR data (1985 – 2010).
- GRACE normal equations to degree and order 160 were taken from the GRGS release 02 GRACE processing (Bruinsma et al. (2010), time span February 2003 – January 2011) together with GRACE normal equations to degree and order 180 from the GFZ release 05 processing (Dahle et al. (2012), time span October 2003 – September 2012). Both normal matrices including their right hand sides were combined, taking degree/order 2–54 from GRGS release 2 and degree/order 55–180 from the GFZ GRACE release 05. Such a blended composition was chosen because the GRGS static coefficients for the wavelengths below degree 55 are more accurate than those of the GFZ release 05. This was verified through GOCE satellite orbit computation. The release 05 normal equation from GFZ is significantly more accurate for degrees 54 and up, which shows as noise reduction over deserts and oceans.
- EIGEN-6S2A contains the same kind of time variable coefficients as EIGEN-6S except for degree 2. For these coefficients the drift as well as the annual and semi-annual parameters were replaced by the ones of a separate LAGEOS processing. Furthermore, a piece-wise linear function plus annual and semi-annual terms were chosen to model these coefficients.
- The GOCE part in EIGEN-6S2A includes the V_{xz} component in addition to V_{xx} , V_{yy} and V_{zz} . It is complete up to degree/order 260. Furthermore during the generation of the observation equations a 120 to 8 second band-pass filter for all four SGG components was applied, which means the SGG signal is now filtered-out below degree about 45.

3.5. *EIGEN-6S2B and the final model EIGEN-6S2*

EIGEN-6S2B is a modified version of EIGEN-6S2A. The modification mainly regards the representation of the drift components for the time variable part of EIGEN-6S2A (degrees 2 to 50). It is based on the assumption

that the non-periodic temporal variation of each time variable spherical harmonic coefficient can be better represented by a series of yearly biases and drifts than by a single mean bias plus drift (which is the case for EIGEN-6S and EIGEN-6S2A), provided that the information is available. This means that the first two summands on the right hand side in Formula 1, i.e. the bias and the drift, are different for each year. The yearly biases and drifts are computed in such a way that they join at each year boundary and form a continuous piece-wise linear function. In addition to these polygons, again annual and semi-annual periodic terms are provided according to Formula 1 for each time spherical harmonic coefficient.

A detailed description of EIGEN-6S2B for degrees 2 and 3-50:

- For the degree 2 coefficients, the SLR satellites LAGEOS-1 and LAGEOS-2 can provide a reasonable knowledge of the time evolution of these parameters. So, from 1985 to 2012, the modeling of the degree 2 coefficients consists of a piece-wise linear term (expressed as an yearly bias plus a drift value) plus a mean periodic solution over the 1985–2012 time span (expressed as a sine and cosine term of the annual and semi-annual variations). The value of the coefficients is obtained by regression on a SLR-only internal solution of Centre National d’Etudes Spatiales (CNES)/GRGS. So, the yearly degree-2 time series of EIGEN-6S2/A/B models is based on SLR from 1985 to 2003 and on GRACE and SLR (GRGS RL02 time series) from 2003 to 2012. Figure 1 compares the GRGS SLR-only $C_{2,0}$ time series with the ones from Cheng and Tapley (Cheng and Tapley, 2004) and Cheng and Ries (Cheng et al., 2013). Figure 1 shows original Cheng et al. time series (black and green lines) and Cheng and Ries time series (cyan line) corrected for the atmosphere and ocean contribution (GAC). The agreement between the GRGS SLR-only $C_{2,0}$ time series (orange line) and Cheng and Ries GAC-corrected time series is rather good. Figure 2 shows again a quite good agreement between the Cheng and Ries original time series with the GRGS GRACE+LAGEOS RL02 times series (with GAC added).

- For the degrees 3 to 50 coefficients the information is only available during the period covered by GRACE (2003–present). So, from 2003 to 2012, the modeling of the coefficients is done in the same way as for degree 2. The value of the coefficients is obtained by regression on the CNES/GRGS RL02 series of GRACE solutions.

The continuity of the yearly gravity solutions is guaranteed by the fact that the original parameters in the regression are the corners (at each 1st of January) of a piece-wise continuous linear function. These parameters are

later translated into yearly bias plus drift, but the continuity is ensured by the original process. However, in some cases when the gravity field undergoes an abrupt change (earthquakes like the ones of Sumatra, Concepcion and Sendai), it can be desirable that the continuity be broken, on the contrary. It is possible with the format that was adopted at the ICGEM to introduce a break at any date within the time series. Such a break was introduced in EIGEN-6S2 and EIGEN-6S2B on 1 January 2005 to account for the Sumatra earthquake (the exact date of the earthquake is 24 December 2004, just one week before the 1st of January).

We have chosen an annual span for the piecewise continuous linear time series for both the GRACE and SLR gravity solutions, since the sub-yearly variations have already been taken into account through the annual and semi-annual periodic parameters. As an illustration, Figure 3 shows the raw time series from SLR-only (in black) and the modeled time series obtained from it (green line) using a yearly bias+drift plus a mean annual and semi-annual periodic model. The variance of the difference between the original series and the modeled series is only 8% of the original signal's variance itself. In order to better stick to reality, an increase in the number of parameters is always conceivable. In particular one could derive the annual and semi-annual parameters for each year instead of computing average ones over 10 years, or swap the periodic parameters for monthly (climatological) parameters. The problem with increasing the number of parameters in mean models is that they become difficult to extrapolate.

The extrapolation of the time variable coefficients outside the included measurement periods (1985 – 2012 for degree 2, 2003 – 2012 for degrees 3 to 50) may propagate an unrealistic gravity field for the unknown past or future, particularly by using the drift values given at the edges of the particular time series. This is a basic issue for time variable gravity field models which cannot be overcome. Therefore we chose the following two options:

- In the case of EIGEN-6S2B all extrapolations were done using a mean drift computed over all included measurement periods.
- We made a modified version of EIGEN-6S2B where the drifts at begin and end of all time series were set to zero. This model is the final gravity field model EIGEN-6S2 which is available for public download at <http://grgs.obs-mip.fr/grace> as well as at the ICGEM data base at GFZ (<http://icgem.gfz-potsdam.de>).

The annual and semi-annual gravity terms differ slightly between EIGEN-6S2 and EIGEN-6S2A/B because in the case of EIGEN-6S2A they were

obtained from a common inversion of the static and time variable parameters contained in the GRGS GRACE contribution to EIGEN-6S2. In the case of EIGEN-6S2 and EIGEN-6S2B they come from a regression on the RL02 GRGS GRACE time series.

4. Influence on the observation residuals, arc overlaps and altimetry crossovers

A whole set of statistical quantities is calculated to evaluate the quality of the derived precise orbits of altimetry satellites Envisat, TOPEX/Poseidon, ERS-1, and ERS-2. In particular, we investigate the impact of the geopotential models on the RMS fits of observations used for precise orbit determination, two-day orbit overlaps in radial, cross-track and along-track directions, but also on the results of single-satellite altimetry crossover analysis, namely, on the RMS and mean of crossover differences computed at 7-day time intervals. The mean values of these quantities are provided in Tables 5–8 and are discussed for each satellite below. The best value for each parameter is marked in bold in these tables. Figures 4–10 show RMS fits of observations for all four satellites as a function of time expressed in the Modified Julian Date (MJD) counted from 1 January 2000, 12 hours (J2000.0). Results showing the impact of different geopotential models on dual-satellite crossovers are described in Sect. 5.

For Envisat, the geopotential models EIGEN-6S_correct, EIGEN-6S2A, EIGEN-6S2 and EIGEN-6S2B provide notably smaller mean values of the quantities given in Table 5 (VER3, VER5–VER7 orbits), as compared to the models EIGEN-GL04S and EIGEN-6S_stat (VER2 and VER4 orbits). Please note that Envisat VER6 and VER7 orbits are virtually almost the same, since the appropriate gravity field models are only different for the period April–December 2002. Thus, the use of new time variable models EIGEN-6S2/A/B reduces the RMS fits of the Envisat SLR observations by 3.6% (0.5 mm) from 1.33 cm (VER2 orbit) to 1.28 cm (VER5–VER7 orbits), when compared to VER2 orbit computed using EIGEN-GL04S. On the contrary, the geopotential model EIGEN-6S_stat significantly (1.85 mm or 12.6%) increases SLR RMS fits (VER4 orbit), especially for the years 2005–2011 (Figure 4), as compared to EIGEN-6S2/A/B, since EIGEN-6S_stat does not take into account linear changes of the geopotential coefficients of degree and order higher than two.

RMS fits of DORIS measurements to Envisat and TOPEX/Poseidon are rather insensitive to the geopotential models tested in this study. This is due mostly to, firstly, the signal-to-noise ratio which is much less favorable than in the case of SLR (the Doppler count is a kind of derivative of the range and therefore the phase detection error at the beginning and at the end of the Doppler count induce a range-rate error that is greater, relatively, than a range measurement error), secondly, the greater number of empirical parameters that are necessary for this radioelectric measurement compared to an optical one (one frequency and one tropospheric bias per pass). These parameters absorb to some extent any mismodeling of the orbit. So, we provide plots for the fits of DORIS observations only for Envisat (Figure 5). However, formally, the geopotential model EIGEN-6S2 and its two pre-versions provide the smallest mean values of RMS fits for DORIS measurements for Envisat (VER5, VER6 and VER7 orbits), and EIGEN-6S2 gives the smallest mean value of RMS fits of DORIS observations for TOPEX/Poseidon (VER6 orbit).

The smallest RMS fits for the SLR observation of TOPEX are obtained using EIGEN-6S2 (cf. Table 6). The use of the model EIGEN-6S.correct gives the largest RMS fits among all tested models for the SLR observations of ERS-1, TOPEX/Poseidon, and ERS-2. The increase of the SLR RMS fits is more prominent at the beginning of the TOPEX/Poseidon mission in 1992–1997 (Figure 6), for the whole ERS-1 mission (1991–1996, Figure 7) and for the period 1995 to about 2002 of the ERS-2 mission (Figure 9), as compared to the SLR RMS fits computed using the geopotential models excluding drifts (like EIGEN-GL04S) or including drifts only for the degree two term until 2003 (like EIGEN-6S2 and EIGEN-6S.stat models). The RMS fits of altimetry crossover observations for VER3 orbit computed using EIGEN-6S.correct geopotential model are larger than those for VER2 and VER6 orbits for ERS-1 (Figure 8) and ERS-2 (Figure 10). This is a good illustration, that the drifts of geopotential coefficients of degree and order 3–50 derived from GRACE (2003–2012) should not be applied to the time before 2003.

The best geopotential model among the herein tested models for TOPEX/Poseidon is EIGEN-6S2. The VER6 orbit of this satellite computed using this geopotential model gives smallest mean values of RMS fits of SLR and DORIS observations, smallest radial and along-track arc overlap, smallest RMS of crossover differences (Table 6) among the TOPEX/Poseidon orbits computed.

A conclusion on the best model for ERS-1 is not as obvious as for TOPEX/Poseidon. As one can see (Table 7), the VER2 orbit gives smallest RMS fits of SLR and altimetry crossover (SXO) measurements, the VER6 orbit gives smallest radial and cross-track arc overlaps, the VER4 orbit provides smallest along-track arc overlaps and RMS of crossover differences, and the VER5 orbit shows smallest mean of crossover differences. So, the geopotential models EIGEN-GL04S, EIGEN-6S_{stat} and EIGEN-6S2 containing zero drifts for degree 3-50 terms perform better than three other models having non-zero drifts for degree 3-50 terms derived from GRACE observations.

For ERS-2, the models EIGEN-GL04S (containing no drift terms for geopotential coefficients) and EIGEN-6S2 (containing no drift terms of degree and order larger than two for the major part of the mission (1995-2003)) provide smaller mean values of the most quantities shown in Table 8, as compared to those obtained using the VER3, VER5 and VER7 orbit geopotential models containing drift terms of degree and order 3-50. So, we conclude that the VER2 and VER6 orbits based on the EIGEN-GL04S and EIGEN-6S2 show better performance than four other orbits for this satellite.

The choice of the gravity field model affects also the values of empirical parameters, such as atmosphere drag coefficients C_d 's and empirical accelerations. The results obtained for Envisat, ERS-1 and ERS-2 – larger affected by non-gravitational perturbations than TOPEX/Poseidon – are provided in Table 9. Figure 11 shows reduction of the variance of atmosphere drag coefficients from 0.038 to 0.029 for Envisat VER5 orbit, as compared to the VER2 orbit.

5. Quality assessment of the different orbit solutions

A multi-mission crossover analysis (MMXO) is used in order to investigate the quality of the different orbit solutions and to check their consistency with other missions. The method takes advantage of the high redundancy provided by a multiple survey of the sea surface through contemporaneous altimeter missions.

For the analysis data from ERS-1, TOPEX/Poseidon, ERS-2, Jason-1, GFO (GEOSAT Follow-On), Envisat, ICESat (Ice, Cloud, and land Elevation Satellite), and Jason-2 are used. The measurements are managed and provided by an open data base for satellite altimeter data (OpenADB, Schwatke et al. (2010)). All data sets are harmonized as far as possible in order to ensure consistent calibration results. Hence, all data refer to identical

reference ellipsoids and time scales and use the same geophysical corrections whenever possible (e.g. ocean tides or inverse barometer effect). However, some differences remain between the missions, mainly due to the lack of dual-frequency ionospheric corrections for ERS and different wet radiometers on board of the satellites.

Six different solutions are computed, each with a different orbit (with a different geopotential model) for the three missions ERS-1, ERS-2 and Envisat. The data from all other missions are not changed between the six solutions. As TOPEX serves as a reference mission an external orbit solution is used to clearly identify the impact of VER2–VER7 orbits on the ESA missions. The TOPEX data are M-GDR (geophysical data records) with Goddard Space Flight Center (GSFC) std0809 orbit (Beckley et al., 2007) and for the Jason mission, GDR-C data with GDR-C orbit (Cerri et al., 2010) are used. The orbits for these two reference missions are based on the ITRF2005 reference frame (Altamimi et al., 2007) and EIGEN-GL04S geopotential model. A test with ITRF2008 TOPEX orbit (VER6) does not show any significant change of the relevant analysis results for ERS and Envisat orbits. Although some of the estimated quantities change by some millimeters (e.g. the differences in the z-component of the origin) they do not influence the main test results. The standard deviation of the estimated radial errors only change by less than 0.5% and the temporal behavior of the y-component differences (c.f. Sect. 5.3) remains stable. Thus, a negative impact of using different reference system realizations is not to be expected.

As the MMXO utilizes sea surface height crossover differences, the analysis provides not only orbit errors but also includes other effects of the instruments (such as range biases) and differences of the geophysical models used.

5.1. Multi-Mission Crossover Analysis

The MMXO is based on the assumption that all altimeter systems observe the same sea surface serving as a relative reference for all investigations. Of course, this only holds for a short period of time so that sea level variations can be neglected. The approach uses single and dual-satellite crossover sea surface height (SSH) differences in all combinations with a maximum time difference of two days. These crossover differences –ideally equal to zero and simply modeled by the difference of two radial error components– are minimized within a least squares adjustment to estimate radial errors of all altimeter systems under investigations. In order to ensure a certain degree

of smoothness of the radial errors the differences of the radial errors of one mission which are neighboring (or close by) in time are also minimized. This supersedes the implementation of an arbitrary analytical function for the temporal behavior of the radial errors.

The problem has a rank defect of 1 and one constraint is necessary to regularize the system. This is done by forcing the mean radial error for one mission (the reference mission) to zero and all other missions are referred to this reference level. It should be emphasized that the reference mission gets non-zero radial errors as any other mission. Only the mean value is forced to zero.

All computations are done in time slots of 14 days (corresponding to the TOPEX/Jason cycles plus some overlaps) to reduce the workload to an acceptable rate. More details on the method can be found in Dettmering and Bosch (2010), Dettmering and Bosch (2013), and Bosch et al. (2013).

The MMXO provides time series of radial errors for each mission involved in the investigations with respect to a reference mission (generally TOPEX or Jason). An assignment of orbital or instrumental causes or deficiencies in geophysical models is not done. The radial errors –which provide upper bounds for the radial orbit errors– will then be used to compute the following derived quantities:

- stochastic properties of the radial errors
- mean range bias (per 10-day cycles and per mission lifetime)
- mean differences in the center-of-origin realization
- geographically correlated errors (GCE)

5.2. Stochastic properties and scatter of the radial errors

The standard deviation of the radial errors serves as an indicator for the quality of the introduced SSH data. Figure 12 shows the scatter for all three missions. It is almost similar for the different orbit solutions. Differences can only be seen in single cycles and at the end of the time series (zoom plot). The EIGEN-6S2/A/B geopotential models (VER5 – VER7 orbits) show better results for all three satellites than the older models (VER2 – VER4 orbits), especially for Envisat. The mean standard deviation of the radial errors for the whole mission lifetime (given in Tab. 10) for the best orbit version reaches 1.6 cm for ERS-1 (VER6 orbit), 2.0 cm for ERS-2 (VER6 orbit), and 1.4 cm

for Envisat (VER5, VER6 and VER7 orbits). The differences between the mission quality are mainly due to the distinct time periods as the scatter is highest in times of high solar activity (2001/2002). As the variations between the different orbit versions are small, no significant impact of the different geopotential models can be detected. However, it seems that the versions behave differently depending on the time periods. This is confirmed by other results in the following subsections (see Sections 5.3 and 5.4).

Empirical auto-covariance functions (EACF) of the radial errors provide additional stochastic properties, especially the temporal correlations of the missions and other useful information on possible systematics of the radial errors. Figure 13 shows the EACF for ERS and Envisat for the six different orbit versions. All EACF have relative maxima after the first and second (and third) orbital revolution due to errors in orbit modeling (1/rev effect) which are higher for ERS-2 than for ERS-1 and Envisat –probably because ERS-2 time period comprises the years 2000-2003 with high solar activity. The solutions for the different orbit versions of one mission do not differ significantly except for ERS-1 for which VER3 and VER4 orbits show worse results than the other four versions.

5.3. Range biases and center-of-origin realization

Within a post-processing step, the radial errors x_i –which depend not only on time but also on position (given by latitude φ and longitude λ)– are separated into range biases (Δr) and center-of-origin shifts (Δx , Δy , Δz). This is done per 10-day cycle by means of a least squares adjustment using the following model (with residuals e_{x_i} accounting for any errors in the input data):

$$x_i + e_{x_i} = \Delta r + \Delta x \cos \varphi \cos \lambda + \Delta y \cos \varphi \sin \lambda + \Delta z \sin \varphi \quad (3)$$

The values Δr mainly represent relative range biases caused by instrument errors such as electronic path delays whereas the center-of-origin shifts reveal systematic differences in the orbit realizations of the different missions. As the absolute reference for the shifts is assigned by the crossover adjustment without fixing the origin for any of the missions, it may not be as reliable as desired. Thus, in order to exclude all effects from the errors in the absolute datum only relative shifts will be interpreted. To be more precise, the (absolute) shifts are computed separately for each satellite and the estimated time series for ERS and Envisat are differenced with the time series

of TOPEX and Jason resulting in relative shifts between the mission under investigation and the reference mission which is assumed to be drift-free.

Tab. 11 summarizes the mean differences in the realization of the origin for all three missions (relative to the reference mission TOPEX/Jason) and for each orbit version. The range biases have only very limited influence on the orbit errors and are not discussed in the following. The small differences between the numbers given in Tab. 11 are probably due to correlation effects between the shifts and the range bias. The center-of-origin differences in the x- and z-components do not show any significant deviations from zero. However, the differences in the y-component are considerably larger and not randomly distributed with time. Systematic errors like this will map into the differences in regional sea level estimates with clearly visible East-West patterns (cf. Section 6.2).

Figure 14 illustrates the temporal systematics of these differences for the three older orbit versions (VER2 – VER4). In the top plot one can see that all three solutions show differences in the realization of the y-component of the origin with respect to the reference mission. The VER2 solution behaves best in the first years but it starts drifting away somewhere around 2005. The same holds for the VER4 orbit solution which also neglects the long-term temporal variations of the gravity field. The VER3 orbit solution behaves better in the actual time span but shows differences in the first years before 1996. The bottom plot of the Figure illustrates the differences between the orbit versions. The two solutions based on the stationary fields show a constant offset of about 7 mm, probably due to the different reference epochs (2004.0 for VER2 orbit and 2000.0 for VER4 orbit). As the VER2 orbit uses the same gravity field as the reference missions it fits better to TOPEX in the first part of the time series. The differences between VER3 and VER4 are almost linear with a trend of about +1.5 mm/year which is due to the different handling of the time variable gravity field (drifts of the degree 3–50 geopotential terms).

It seems that using only the drift terms of the EIGEN-6S geopotential coefficients determined using GRACE data at the time interval 2003 – 2008 (like in VER3) is not advisable for POD outside this time interval (i.e. ERS-1 mission time). This was the motivation to compute the three other orbit versions based on the EIGEN-6S2/A/B gravitational fields (VER5 – VER7 orbits). The relative center-of-origin differences in the y-component for these orbits are plotted in Figure 15. It can be clearly seen that only the VER6 orbit solution is able to give a time series without significant drift and to

provide consistent results for all three missions (ERS-1, ERS-2 and Envisat).

5.4. Geographically correlated errors

Error components having the same sign for ascending and descending passes are called geographically correlated errors. The MMXO is able to reveal GCE from the estimated radial errors for each mission involved. GCE mainly represent problems in precise orbit determination, e.g. reference frame differences or gravitational effects, but also include other geographically correlated effects. For the computation the range bias for each 10-day cycle (which is mainly satellite-specific) has been subtracted from the radial errors in order to show only the geographical variations. The remaining radial errors were gridded and averaged separately for ascending and descending passes (Δr^{asc} , Δr^{desc}) and then used to compute the mean error $\Delta\gamma$ following Rosborough (1986):

$$\Delta\gamma = (\Delta r^{asc} + \Delta r^{desc})/2 \quad (4)$$

GCE are an important error component as they are not visible in single-satellite crossover analysis but map directly in the sea surface height determination and the derivation of sea level trends. Figure 16 shows the resultant maps of GCE for the three missions (ERS-1 on the left, ERS-2 in the middle, and Envisat on the right) for all six orbit solutions. All GCE remain smaller than approximately 2 cm. The RMS values range between 2.8 and 5.1 mm (see Tab. 12). Which orbit version behaves best depends on the mission, respectively on its time period. The best results can be reached for ERS-1 with VER6 (± 2.8 mm RMS), for ERS-2 with VER5 (± 3.6 mm RMS), and for Envisat with VER6 orbits (± 2.9 mm RMS). For some orbit versions clear systematics effects can be seen (e.g. VER4 for Envisat) which clearly illustrates the mean center-of-origin shifts given in Tab. 11. Since GCE are computed as mean over the whole mission’s lifetimes, no time dependant effects are visible. The VER6 orbit ensures minimal GCE without systematic effects for all three missions.

6. Impact on the estimation of global and regional sea level trends

The impact of the VER2 to VER7 orbit solutions on the global and regional mean sea level is evaluated in this Section. In Sections 4 and 5 the quality of the different orbit solutions has been evaluated by means of various

statistical criteria. The main focus here is on the impact of the drifts of the degree 2–50 terms of new time variable geopotential models on the sea level data. While until recently altimeter orbits have been based on the EIGEN-GL04S model (Jason GDR-C standards, Cerri et al. (2010)), the new GDR-D standards orbits (OSTM/Jason-2 Products Handbook, 2011) are based on the models comparable to EIGEN-6S. Important questions are whether the implementation of the drifts of the geopotential coefficients infers with the estimation of the global and regional sea level trends on climate scales and how reliable these drifts over the course of the last two decades are. Hence, the trends over the full duration of the missions (between 4 and 12 years) in dependance of the orbit model are analyzed and the consistency of the sea level data originating from different missions is investigated.

6.1. Impact on the global mean sea level trends

Global mean sea level (GMSL) for the area between 66°S and 66°N has been calculated from the along-track geophysical data records originating from the ERS-1, ERS-2, TOPEX, and Envisat missions based on the six orbit solutions VER2 to VER7 and is shown in Figure 17. The different orbit solutions have no significant effects on the GMSL – neither on the variability nor on the trends. From the GMSL time series a trend has been estimated for each of the four missions by fitting a mission-long trend together with the annual and semi-annual signals. The corresponding trend ranges and the standard deviations of the fitted trend values are given in Table 13. There are considerable differences of the GMSL trends derived from the four missions which are related to the measurements themselves and the periods covered. However, the differences in the GMSL trends related to the choice of orbits are not significant since they are consistently within the error bounds of the applied least-squares fit.

A more detailed analysis of the GMSL has been performed for a subset of three orbit solutions for ERS-2. Here, the GMSL time series has been calculated from grids of sea level height of $2^\circ \times 2^\circ$ for each 35-day ERS-2 cycle (Ablain et al., 2009) based on three ERS-2 orbit solutions (VER2, VER3, VER4) and plotted in Figure 18. The trend deduced from these three curves is very consistent and close to 2.5 mm/year from 1995 to 2003 since the observed differences are lower than 0.1 mm/year which is not significant over such a short period.

6.2. Impact on regional sea level trends

The analyses in Section 5.3 show relative shifts of the center-of-origin of the ERS-1, ERS-2 and Envisat missions w.r.t. the reference missions TOPEX and Jason-1/2 in dependance of the orbit solutions used. These relative shifts of the center-of-origin are caused by the inclusion of the drift terms for the coefficients of the geopotential model underlying the orbit solution. Such drifts of the center-of-origin will result in apparent changes of regional sea level trends. In the following we are focusing on changes in regional sea level trends arising when introducing interannual changes to the $C_{2,0}$ term and drifts for the degree 3–50 terms. Therefore, we proceed in two steps: first we analyse the regional trends between the difference of the radial components for the orbits solutions VER2 and VER4 and for VER2 and VER3. Afterwards we check the consistency of the sea level anomalies estimated independently from various missions for time slices at the beginning and at the end of the 20-year series of altimetry based on the different orbit solutions.

6.2.1. Radial orbit differences

We map the differences of the radial components of the six orbit solutions for each of the four satellites to $1^\circ \times 1^\circ$ grids – every 9.92 days for TOPEX and every 35 days for ERS-1, ERS-2 and Envisat. From the time series of the radial orbit differences we estimate local trends and annual and semi-annual signals using a least-square fit. To allow the reader to relate the trend differences which are discussed in the following to the absolute trend values, a map of the regional sea level trends derived from ERS-2 and Envisat data based on VER6 orbits for the period from May 1995 to October 2010 is shown in Figure 19.

The trends derived from the *VER4 minus VER2* orbit differences are shown in Figure 20. The only plausible source of the interannual trends between the VER2 and the VER4 orbits is the inclusion of interannual changes of the C_{20} term in the EIGEN-6S_stat model which was used to calculate the VER4 orbits. For these two orbit solutions the differences in the regional sea level trend are small. For TOPEX they are close to zero, for ERS-1, ERS-2 and Envisat the trends range between ± 0.5 mm/year with centers around 140°E and 40°W . They are suggestive of small drifts of the center-of-origin in all three components. These small differences are consistent with the results in Section 5.3, Figure 14 where almost no drift in the y-component of the center-of-origin can be seen but only a small offset between the different orbit solutions.

The trend differences derived from the *VER3 minus VER2* orbits (Figure 21) show a dipole pattern with centers in the Tropical Indian and the Eastern Tropical Pacific Oceans. The trend-values reach extrema of more than ± 2.5 mm/year and hint to a relative drift of the center-of-origins of the VER3 and VER2 orbit solutions mainly along the y-component (i.e. East-West) of the reference system. Very similar patterns can be observed for other orbit differences (e.g. VER3 to VER4, VER5 to VER2 and VER7 to VER2, not shown) and can be related to the in- or exclusion of drifts for the degree 3–50 terms in the geopotential models used. While the trend-patterns of ERS-1, ERS-2 and Envisat orbit differences are very similar to each other, the trends for the TOPEX orbit differences show a similar pattern but of reversed sign, that can possibly be explained by the orbit inclination of these satellites. While the TOPEX/Poseidon orbit is prograde (66°), the inclination of ERS-1, ERS-2 and Envisat orbits is retrograde (98.5°). A more detailed investigation of the perturbations exerted by the drifts of the geopotential coefficients (Rosborough and Tapley, 1987) for the different orbit geometries is necessary to decide on the source of this effect.

All the orbit solutions based on the geopotential models including drifts for the degree 3–50 terms (VER3, VER5, VER6 and VER7) show all very similar results for Envisat and hence only minor trend differences (not shown). However, different approaches were chosen for the estimation of the degree 3–50 term drifts for the pre-GRACE period. The VER3, VER5 and VER7 orbits are all based on the models including (differing) drifts of the degree 3–50 terms and are all very close to each other for ERS-1, ERS-2 and TOPEX. For the calculation of the VER6 orbits no drifts of the degree 3–50 geopotential terms are used outside the GRACE period and there are only very small radial trends between the VER2/VER4 and VER6 orbits in the pre-GRACE period (Figure 22). This result corroborates and illustrates the results from Section 5.3, cf. Figures 14 and 15.

6.2.2. Regional mean sea level differences

Significant differences in the radial orbit components up to ± 3 mm per year arise from the choice of the orbit solution and will result in apparent regional sea level trends which are of the same order as the total signal in some regions (e.g. eastern Tropical Pacific and south of Australia). Therefore, it is necessary to further evaluate the quality and long term consistency of the orbits derived from static and time variable gravity fields. As the center-of-origin of the orbits for TOPEX on the one side and ERS-1, ERS-2, Envisat

on the other side seem to drift in opposite directions we have checked the consistency of temporal mean sea level patterns at different periods derived from the available missions for all six orbit solutions. Yearly mean sea level anomalies have been calculated for the period June 1995 to May 1996 for ERS-1, ERS-2 and TOPEX and for the period October 2002 to September 2003 for TOPEX, ERS-2 and Envisat. The results documented in Section 5.3 suggest that the orbit solutions VER2 to VER4 are diverging at the end of the time series. Since there are presently no orbit solutions from GFZ corresponding to VER2 – VER7 orbits available for Jason-1 or Jason-2 we have included GDR-C (CNES) and GDR-D (ESOC, Otten et al. (2010)) orbits for Jason-2 in our analysis to compare yearly sea level anomalies originating from Envisat and Jason-2 for 2010.

The altimetry data has been retrieved from the GFZ’s ADS system and is corrected using state-of-the-art harmonized correction models. The yearly mean sea level anomalies have been mapped to a $1^\circ \times 1^\circ$ grid.

The sea level differences for 1995/1996 between ERS-2 and TOPEX are shown in Figure 23, the differences between the ERS-1 and TOPEX sea levels are similar (not shown). There is a clear dipole pattern with extrema of ± 5 cm visible for the ERS-1/ERS-2 and TOPEX sea level differences for the VER3, VER4, VER5 and VER7 but not for the VER2 and VER6 orbit solutions. This suggests that the VER2 and VER6 orbit solutions are most consistent for the period 1995/1996. This can also be seen while comparing VER2 and VER6 center-of-origin trends for the relevant time periods in Figures 14 and 15.

The picture is not as clear for the sea level differences in 2002/2003 between Envisat and TOPEX shown in Figure 24 for VER2, VER3 and VER4 and between ERS-2 and TOPEX (similar, not shown). The mean sea level computed using the VER5, VER6 and VER7 orbit solutions (not shown) are very close to those computed using the VER3 solution. During this later period almost all orbit solutions seem to perform equally well. This period is close to the reference epoch of most of the geopotential models used. The only exception is the VER4 orbit solution (reference epoch 2000.0) which exhibits a dipole pattern with extrema of ± 3 cm with centers in the western Tropical Indian Ocean and the eastern Tropical Pacific Ocean. This result is consistent with the findings in Section 5.

The sea level differences for 2010 between Envisat and Jason-2 are shown in Figure 25. The Envisat and Jason-2 sea level differences are dominated by a dipole pattern with extrema of ± 1 cm for the VER2 and GDR-C but

not for the VER3 and GDR-D orbit solutions. The additional North/South differences in the VER3 and GDR-D differences are most probably related to small differences in the realization of the reference frames. The differences between the VER3, VER5 and VER6 orbit solutions are too small to be evaluated on this qualitative basis. This suggests that the VER3/VER5 and VER6 orbit solutions are most consistent for the period 2010. This can also be seen comparing the VER2 and VER6 center-of-origin trends for the relevant time periods in Figures 14 and 15.

6.2.3. Discussion

From the orbit differences based on the two stationary geopotential models (EIGEN-GL04S, EIGEN-6S_stat) minor drifts of the centers-of-origin up to ± 0.5 mm/year can be identified for ERS-1, ERS-2 and Envisat. They are most probably related to the C_{20} drift term (included in EIGEN-6S_stat but not in EIGEN-GL04S). Even though the VER4 orbits are based on the newer geopotential model and the C_{20} drift term is known quite accurately they are less consistent than the VER2 orbit solutions throughout the missions for all periods analyzed (1995/1996, 2002/2003, 2010). The most plausible explanation for this is a degradation of EIGEN-6S_stat by the transformation to its reference epoch (2000).

There are relative drifts of the centers-of-origin between the orbit solutions based on the time variable (EIGEN-6S, EIGEN-6S2) and on the stationary geopotential models (EIGEN-6S_stat, EIGEN-GL04S). These drifts are equivalent to the regional sea level trends up to ± 3.0 mm/year. Obviously, the drifts of the degree 3–50 terms of the time variable geopotential models seem to be transformed to drifts of the center-of-origin of the derived orbits – mainly along the y-axis. Since Cerri et al. (2013) are able to reproduce similar patterns by the inclusion of the time variable gravity terms up to degree and order 4, the source for the apparent drifts of the centers-of-origin is most probably in the low degree drift terms of the geopotential models. The drifts of the orbits’ centers-of-origin seem to be dependent on the orbit configuration (altitude, inclination) and have opposite signs for the ERS-1, ERS-2 and Envisat series on the one side and those of TOPEX on the other side. While this analysis hints at possible spurious regional trends in long sea level time series from combined altimetry, it does not allow to select the best orbit solution for the provision of long and consistent regional sea level time series for climate studies. For the last decade recent studies have shown that satellite orbits based on EIGEN-6S are superior to those based

on EIGEN-GL04S. Ollivier et al. (2012) have shown an enhanced agreement between Envisat and Jason-1/Jason-2 altimetry results and Valladeau et al. (2012) find better accordance between Envisat and in-situ Argo temperature and salinity profiles. Our analyses show for 1995/1996 the best coincidence between TOPEX and ERS-1/ERS-2 when using orbits based on EIGEN-GL04S and EIGEN-6S2, i.e. models without drifts of the degree 3–50 terms for the pre-GRACE period. This suggests either that there were no relevant drifts of the degree 3–50 terms in the pre-GRACE period or that they cannot yet be estimated with sufficient accuracy. For this period also no ARGO data is available for validation. Comparisons to tide gauge data at regions with maximum trend differences of the radial orbit differences might be an alternative. However, recent analyses of Zelensky et al. (2012) show much stronger variability of the sparsely distributed residuals from tide gauges and altimetry than from the radial orbit differences. For 2010 we find the best coincidence between Jason-2 and Envisat for orbits based on geopotential models including drifts of the degree 2–50 terms. The VER3, VER5 and VER6 orbits perform comparably well for this particular year.

7. Conclusions and outlook

During the last decade Earth’s gravity field models have been improved tremendously. The quality of altimetry satellite orbits and hence of sea level data benefits from this progress. While until recently the model EIGEN-GL04S was the base for state-of-the-art orbit modeling (Cerri et al., 2010), new orbits are based on time variable gravity field models as EIGEN-6S including drifts of the coefficients for degree 2–50 (OSTM/Jason-2 Products Handbook, 2011). We have studied the influence of these new models on the precise orbits of ERS-1, ERS-2, TOPEX/Poseidon, and Envisat and on regional sea level trends based on these orbits. Our studies are based on two stationary (EIGEN-GL04S and EIGEN-6S_{stat}) and four time variable (EIGEN-6S_{correct}, EIGEN-6S2A, EIGEN-6S2 and EIGEN-6S2B) geopotential models. On the one hand this allows us to specify the impact of the consideration of drift terms for the degrees 3–50. On the other hand with the newly developed EIGEN-6S2/A/B models we are able to study the effects of an advanced modeling by including the degree 2–50 drift terms and of alternative approaches for the extrapolation of the drift terms for the pre-GRACE period. In order to assess the quality of the orbits derived from the various geopotential models statistics of tracking observations as well

as single-mission crossover (SMXO, Section 4) and multi-mission crossover (MMXO, Section 5) statistics have been applied. Besides the reduction of the associated RMS values the focus was on the generation of reliable and long term stable regional sea level trends (Section 6).

We have found that the modeling of time variable gravity improves the orbit solutions, at least for those periods for which time variable gravity can be sufficiently accurately observed at the periods covered by GRACE measurements. For the GRACE-period from 2003 onwards analyses of (Ollivier et al., 2012) have shown that orbits based on a model similar to EIGEN-6S are superior to such based on EIGEN-GL04S. This result is proved by our statistics of the tracking observations when using all four time variable geopotential models tested, the SMXO and the MMXO as well as by intermission comparisons for Envisat and Jason-2. The differences between the orbits based on EIGEN-6S_correct and EIGEN-6S2 are rather small for 2003 onwards. The results of the MMXO analysis, however, indicate that the orbits based on EIGEN-6S2 and its two precursors EIGEN-6S2A/B perform better than those based on EIGEN6S_correct – especially towards the end of the Envisat mission.

However, for the pre-GRACE period the orbits based on stationary geopotential models without drift terms for the degree 3–50 terms (EIGEN-GL04S, EIGEN-6S_stat) and EIGEN-6S2 perform superior to the ones including drift terms for this period (EIGEN-6S_correct, EIGEN-6S2A/B). This finding is indicated by our statistics of the tracking observations, the SMXO and the MMXO and by intermission comparisons for ERS-1, ERS-2 and TOPEX. The MMXO analyses suggest that the orbits based on EIGEN-6S2 have the smallest radial and geographically correlated errors. This indicates that the application of the linear trends of the spherical harmonic coefficients of degree 3–50 which are based on GRACE data between 2002 and 2012 degrades the orbit quality when extrapolating before the GRACE launch, i.e. from 1991 till 2002.

The main effect of the inclusion of the drifts for the degree 3–50 terms is an apparent drift of the center-of origin between the derived orbits - mainly along the y-axis. According to (Cerri et al., 2013) these patterns might be related to mass changes at Greenland and West-Antarctica. Even though the MMXO shows apparent origin offsets up to 2 cm at the beginning of the ERS-1 mission, the different orbit solutions have no influence on the computed global mean sea level trend for any of the four missions under investigation (Section 6.1). However, strong East/West differences up to

3 mm/year were found in regional mean sea level trends, while using orbits based on different geopotential models (cf. Section 5.3). These drifts appear to be dependent on the orbit configuration (altitude, inclination) and have opposite signs for the ERS-1, ERS-2 and Envisat series on the one side and those for TOPEX on the other side (Section 6.2.1).

From our analysis, we conclude, that the time variable geopotential model EIGEN-6S2 performs best among the herein studied models. It provides reliable and consistent sea level estimates for the whole time period from 1992 to 2010. In contrast to EIGEN-6S2A, the model EIGEN-6S2 contains yearly time series for the drifts of all spherical harmonic coefficients for the degrees 3 to 50 for the GRACE period (2003 – 2012) and zero drifts outside this period for these coefficients. Both models EIGEN-6S2A and EIGEN-6S2 contain a time series of the drifts of three degree 2 geopotential coefficients for the period 1985 to 2012. However, more refined time variable geopotential modeling is still needed for the time span from 1985 till 2003. Probably, this could be achieved using SLR measurements to LAGEOS-1/2, Stella, Starlette and DORIS measurements to TOPEX/Poseidon and some other satellites to create a more precise time variable geopotential model for this time interval.

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Table 1: The main models and input data used for precise orbit determination.

Reference System	
Polar motion and UT1	IERS EOP 08 C04 (IAU2000A) series with IERS daily and sub-daily corrections
Precession and Nutation model	IERS Conventions (2010)
SLR station coordinates	ITRF2008 (Altamimi et al., 2011), SLRF2008 (Pavlis, 2009) for missing stations
DORIS station coordinates	ITRF2008 (Altamimi et al., 2011) and DPOD2008 (Willis et al., 2009) (http://www.ipgp.fr/~willis/DPOD2008/) for missing stations
PRARE station coordinates	GFZ, estimated at each arc
Displacement of reference points	
Solid Earth tides	IERS Conventions (2010)
Atmospheric loading	GFZ, based on European Centre for Medium-Range Weather Forecasts (ECMWF) atmosphere data
Ocean loading	GFZ, based on FES2004 (Letellier, 2004) ocean tide mode
Solid Earth pole tide	IERS Conventions (2010)
Ocean pole tide	IERS Conventions (2010)
Gravity	
Gravity field (static)	see Section 3
Gravity field (time varying)	see Section 3
Solid Earth tides	IERS Conventions (2010)
Pole tide	IERS Conventions (2010)
Ocean tides	EOT10A (Mayer-Gürr et. al., 2012), all constituents up to degree and order 50
Atmospheric tides	Biancale and Bode (2006)
Non-tidal atmospheric and oceanic gravity	ECMWF 6-hourly fields up to degree and order 50 (Dobslaw et al., 2013)
Third bodies	Sun, Moon, Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto (DE-421) (Folkner et al., 2009)
Surface forces and empirical	
Radiation pressure model	GFZ EPOS-OC box/wing model
Radiation pressure scale coefficient	Fixed (1.07)
Earth radiation	Knocke and Ries (1987)
Atmospheric density model	MSIS-86 (Hedin, 1987)
Drag coefficients	adjusted 4–8 times a day
Once per revolution empiricals	estimated every 12–24 hours

Table 2: The main models and input data used for precise orbit determination (continue).

SLR measurements	
Data taken from	U.S. National Aeronautics and Space Administration (NASA) Crustal Dynamics Data Information System (CDDIS), International Laser Ranging Service (ILRS) (Pearlman et al., 2002)
Troposphere correction	IERS Conventions (2010)
Retroreflector correction	Fixed offset value per satellite according to ILRS website values
Elevation cutoff angle	10°
DORIS measurements	
Data taken from	International DORIS Service (IDS) (Willis et al., 2010)
Troposphere correction	(Hopfield, 1969) model
Elevation cutoff angle	10°
PRARE measurements	
Data taken from	GFZ
Troposphere correction	Davis et al. (1985)
Retroreflector correction	fixed pre-launch offset values
Elevation cutoff angle	10°
Altimeter data	
Data taken from	ADS Database (Schöne et al., 2010), single satellite altimetry crossover data
Dry troposphere correction	ECMWF model for Envisat, TOPEX, French Met fields for ERS-1 and ERS-2
Wet troposphere correction	Microwave radiometer
Ionosphere correction	NIC09 model (Scharroo and Smith, 2010) used for ERS-1/2, Jet Propulsion Laboratory (JPL) Global Ionosphere Maps (GIM) used for Envisat
Inverse barometric correction	Scaled version of relative inverse barometer before 1992, MOG2D thereafter
Solid Earth tide	IERS Conventions (2010)
Ocean tide	GOT4.7 tidal model, an update to (Ray, 1999)
Load tide	GOT4.7 tidal model, an update to (Ray, 1999)
Pole tide	EOP (IERS) 08 C04
Sea state bias	BM4 (Gaspar and Ogor, 1996)
Relativistic corrections	IERS Conventions (2010)

Table 3: The main characteristics of the used geopotential models.

Parameter	EIGEN-GL04S (VER2)	EIGEN-6S_correct (VER3)	EIGEN-6S_stat (VER4)
Maximum degree and order	150	240	240
Truncation level	90	90	90
Reference epoch	01.01.2004	01.01.2005	01.01.2000
$\bar{C}_{2,0}$	$-0.484165281 \times 10^{-3}$	$-0.484165300 \times 10^{-3}$	$-0.484165316 \times 10^{-3}$
Drifts of coefficients	no	constant drift for degree 2–50 terms	constant drift only for $\bar{C}_{2,0}$ term
$\dot{\bar{C}}_{2,0}$	0.0	$3.182710000 \times 10^{-12}$	$3.18271000 \times 10^{-12}$
$\Delta\bar{C}_{2,0}$ correction to EIGEN-6S model	0.0	see Formula 2	see Formula 2
Annual and semi- annual variations	for degree 2–50 terms	for degree 2–50 terms	for degree 2–50 terms
IERS Conventions	2003	2003	2003

Table 4: The main characteristics of the used geopotential models (continue).

Parameter	EIGEN-6S2A (VER5)	EIGEN-6S2 (VER6)	EIGEN-6S2B (VER7)
Maximum degree and order	260	260	260
Truncation level	90	90	90
Reference epoch	coefficient specific constant	coefficient specific constant	coefficient specific constant
$\bar{C}_{2,0}$ (1950-1985)	constant	constant	constant
$\bar{C}_{2,0}$ (1985-2012)	a yearly time series	a yearly time series	a yearly time series
$\bar{C}_{2,0}$ (2012-2050)	constant	constant	constant
$\dot{\bar{C}}_{2,0} - \dot{\bar{S}}_{2,2}$ (1950-1985)	0.0	0.0	0.0
$\dot{\bar{C}}_{2,0} - \dot{\bar{S}}_{2,2}$ (1985-2012)	a yearly time series	a yearly time series	a yearly time series
$\dot{\bar{C}}_{2,0} - \dot{\bar{S}}_{2,2}$ (2012-2050)	0.0	0.0	0.0
$\dot{\bar{C}}_{3,0} - \dot{\bar{S}}_{50,50}$ (1950-2003)	constant	0.0	constant
$\dot{\bar{C}}_{3,0} - \dot{\bar{S}}_{50,50}$ (2003-2012)	constant	a yearly time series	a yearly time series
$\dot{\bar{C}}_{3,0} - \dot{\bar{S}}_{50,50}$ (2012-2050)	constant	0.0	constant
Annual and semi- annual variations	for degree 2–50 terms	for degree 2–50 terms	for degree 2–50 terms
IERS Conventions	2010	2010	2010

Table 5: Envisat (2002 to 2011): the mean values of RMS fits of SLR and DORIS observations, radial, cross-track and along-track arc overlaps, RMS and mean of crossover differences. The total number of the orbital arcs used to compute these mean values is 662 for SLR observations, 648 for DORIS observations and 525 for arc overlaps. The crossover statistics was computed over 444 weeks from 14 May 2002 till 28 December 2010.

Orbit version	SLR RMS fits [cm]	DORIS RMS fits [mm/s]	Radial arc overlap [cm]	Cross- track overlap [cm]	Along- track overlap [cm]	Cross- over RMS [cm]	Cross- over mean [cm]
VER2	1.327	0.4318	0.594	2.167	2.292	5.951	0.477
VER3	1.281	0.4316	0.534	2.149	2.190	5.925	0.431
VER4	1.464	0.4335	0.814	2.293	2.803	5.964	0.588
VER5	1.279	0.4315	0.532	2.139	2.222	5.925	0.440
VER6	1.279	0.4315	0.527	2.118	2.251	5.927	0.442
VER7	1.280	0.4315	0.527	2.118	2.256	5.927	0.443

Table 6: TOPEX/Poseidon (1992 to 2005): the mean values of RMS fits of SLR and DORIS observations, radial, cross-track and along-track arc overlaps, RMS and mean of crossover differences. The total number of the orbital arcs used to compute these mean values is 494 for SLR observations, 459 for DORIS observations and 433 for arc overlaps. The crossover statistics was computed over 640 weeks from 9 April 1993 till 30 September 2005.

Orbit version	SLR RMS fits [cm]	DORIS RMS fits [mm/s]	Radial arc overlap [cm]	Cross- track overlap [cm]	Along- track overlap [cm]	Cross- over RMS [cm]	Cross- over mean [cm]
VER2	2.032	0.4798	1.023	6.524	3.663	5.313	-0.330
VER3	2.083	0.4803	1.060	6.576	3.701	5.347	-0.081
VER4	2.054	0.4799	1.046	6.559	3.777	5.342	-0.063
VER5	2.054	0.4800	1.036	6.554	3.632	5.326	-0.254
VER6	2.022	0.4797	1.021	6.533	3.590	5.307	-0.294
VER7	2.045	0.4799	1.036	6.543	3.625	5.319	-0.228

Table 7: ERS-1 (1991 to 1996): the mean values of RMS fits of SLR and SXO observations, radial, cross-track and along-track arc overlaps, RMS and mean of crossover differences. The total number of the orbital arcs used to compute these mean values is 376 for SLR observations, 362 for SXO observations and 284 for arc overlaps. The crossover statistics was computed over 200 weeks from 9 July 1992 till 30 May 1996.

Orbit version	SLR RMS fits [cm]	SXO RMS fits [cm]	Radial arc overlap [cm]	Cross- track overlap [cm]	Along- track overlap [cm]	Cross- over RMS [cm]	Cross- over mean [cm]
VER2	2.146	4.735	3.626	18.524	16.248	6.020	0.148
VER3	2.233	4.828	3.444	19.909	16.855	6.074	0.122
VER4	2.148	4.752	3.410	19.580	16.029	6.009	0.150
VER5	2.219	4.843	3.497	18.473	16.682	6.072	0.096
VER6	2.162	4.786	3.405	17.716	16.244	6.018	0.244
VER7	2.205	4.801	3.466	19.228	16.087	6.053	0.171

Table 8: ERS-2 (1995 to 2006): the mean values of RMS fits of SLR, SXO, PRARE range and PRARE Doppler observations, radial, cross-track and along-track arc overlaps, RMS and mean of crossover differences. The total number of the orbital arcs used to compute these mean values is 793 for SLR observations, 779 for SXO observations, 258 for PRARE observations and 596 for arc overlaps. The crossover statistics was computed over 549 weeks from 15 May 1995 till 20 February 2006.

Orbit version	SLR RMS fits [cm]	SXO RMS fits [cm]	PRARE range RMS fits [cm]	PRARE Doppler RMS fits [mm/s]	Radial arc overlap [cm]	Cross- track arc overlap [cm]	Along- track arc overlap [cm]	Cross- over RMS [cm]	Cross- over mean [cm]
VER2	1.684	4.098	3.458	0.3932	1.936	7.239	11.0867	6.462	0.143
VER3	1.740	4.129	3.497	0.3969	1.986	7.409	10.972	6.465	0.147
VER4	1.724	4.135	3.475	0.3949	1.999	7.506	11.080	6.470	0.222
VER5	1.733	4.130	3.482	0.3955	1.982	7.397	11.291	6.483	0.128
VER6	1.696	4.099	3.456	0.3931	1.932	7.356	11.305	6.464	0.190
VER7	1.727	4.120	3.485	0.3956	1.962	7.408	11.190	6.467	0.189

Table 9: Variance of atmosphere drag coefficients and cosine cross-track (cosN) empirical acceleration for ERS-1, ERS-2, Envisat VER2–VER7 orbit solutions.

Orbit version	ERS-1 Cd variance	ERS-1 cosN variance [m2/s4]	ERS-2 Cd variance	ERS-2 cosN variance [m2/s4]	Envisat Cd variance	Envisat cosN variance [m2/s4]
VER2	0.0876	0.1224 $\times 10^{-12}$	0.0694	0.1676×10^{-13}	0.0375	0.8554×10^{-17}
VER3	0.0910	0.1448×10^{-12}	0.0707	0.1190 $\times 10^{-13}$	0.0299	0.8354×10^{-17}
VER4	0.0874	0.1448×10^{-12}	0.0701	0.1254×10^{-13}	0.0469	0.8506×10^{-17}
VER5	0.0932	0.1484×10^{-12}	0.0716	0.1372×10^{-13}	0.0294	0.8077 $\times 10^{-17}$
VER6	0.0895	0.1464×10^{-12}	0.0697	0.1374×10^{-13}	0.0294	0.8123×10^{-17}
VER7	0.0935	0.1555×10^{-12}	0.0717	0.1390×10^{-13}	0.0294	0.8122×10^{-17}

Table 10: Mean scatter of radial errors [cm]. The best results are marked with bold numbers.

Satellite	VER2	VER3	VER4	VER5	VER6	VER7
ERS-1	1.68	1.75	1.69	1.63	1.57	1.64
ERS-2	2.11	2.12	2.11	2.03	2.02	2.03
Envisat	1.55	1.52	1.65	1.40	1.41	1.41

Table 11: Global mean range bias and center-of-origin shifts for satellites ERS-1 and ERS-2 relative to TOPEX and for Envisat relative to Jason-1 using six different orbits, in [mm]. Shifts with considerable higher values than standard deviations are marked with **bold numbers**.

Satellite orbit	Δr_{rel}	Δx_{rel}	Δy_{rel}	Δz_{rel}
ERS-1 VER2	442.0 ± 7.6	0.9 ± 3.2	0.7 ± 2.7	-2.3 ± 5.1
ERS-1 VER3	442.8 ± 7.3	-0.3 ± 3.3	-12.4 ± 4.0	-0.3 ± 5.3
ERS-1 VER4	442.3 ± 7.6	0.4 ± 3.0	-5.6 ± 3.0	-1.3 ± 5.4
ERS-1 VER5	443.7 ± 7.8	1.9 ± 2.8	-11.0 ± 3.6	-0.3 ± 5.1
ERS-1 VER6	443.3 ± 7.9	2.0 ± 3.1	0.6 ± 2.6	-2.5 ± 4.8
ERS-1 VER7	443.9 ± 7.6	1.6 ± 2.8	-10.2 ± 3.4	-1.3 ± 5.1
ERS-2 VER2	71.1 ± 6.7	0.0 ± 6.4	1.4 ± 5.0	-3.4 ± 7.4
ERS-2 VER3	71.1 ± 6.7	-0.8 ± 6.5	-5.7 ± 5.7	-2.2 ± 7.5
ERS-2 VER4	71.1 ± 6.6	-0.8 ± 6.4	-5.3 ± 5.5	-2.4 ± 7.3
ERS-2 VER5	71.5 ± 6.7	0.5 ± 5.2	-4.7 ± 5.2	-2.1 ± 7.3
ERS-2 VER6	71.3 ± 6.8	0.8 ± 6.3	1.2 ± 4.6	-3.4 ± 7.2
ERS-2 VER7	71.5 ± 6.7	0.7 ± 6.3	-3.4 ± 5.2	-2.8 ± 7.3
Envisat VER2	350.8 ± 6.8	-0.2 ± 3.5	-4.3 ± 5.2	0.3 ± 3.8
Envisat VER3	350.5 ± 6.9	0.1 ± 3.4	-1.6 ± 3.5	0.2 ± 3.6
Envisat VER4	351.0 ± 6.7	-2.1 ± 4.2	-12.1 ± 5.8	1.0 ± 3.7
Envisat VER5	351.4 ± 7.5	0.0 ± 3.1	-0.7 ± 3.2	0.4 ± 3.2
Envisat VER6	351.4 ± 7.6	-0.0 ± 3.1	-0.6 ± 3.1	0.3 ± 3.2
Envisat VER7	351.4 ± 7.6	-0.0 ± 3.1	-0.6 ± 3.1	0.3 ± 3.2

Table 12: RMS of geographically correlated errors [mm]. The best results are marked with bold numbers.

Satellite	VER2	VER3	VER4	VER5	VER6	VER7
ERS-1	3.0	3.7	3.1	3.2	2.8	3.2
ERS-2	3.8	4.0	4.1	3.6	3.6	3.6
Envisat	3.2	2.9	5.0	2.9	2.9	2.9

Table 13: Range of the global mean sea level trends [mm/year] for ERS-1 (1992 to 1996), ERS-2 (1995 to 2003), TOPEX (1993 to 2005), and Envisat (2002 to 2010) for the region 66°S/N based on the orbit solutions VER2 to VER7. The formal errors of the least-squares fit are given in brackets. A GIA correction of 0.3 mm/year has been added.

ERS-1	ERS-2	TOPEX	Envisat
5.0 – 5.1(± 0.5)	2.5 – 2.7(± 0.2)	3.4 – 3.5(± 0.1)	2.8 – 3.0(± 0.2)

Figure 1: SLR-only time series of $C_{2,0}$ geopotential coefficient.

Figure 2: Comparison of the time series of $C_{2,0}$ geopotential coefficient from Cheng and Ries (green line) and from GRGS RL02 (with GAC added, pink line).

Figure 3: Comparison of the GRGS LAGEOS-1&2 solution of $C_{2,0}$ time series with the full model (piece-wise linear (PWL) and average periodic terms).

Figure 4: RMS fits of SLR observations for Envisat orbits from 12 April 2002 till 2 January 2011.

Figure 5: RMS fits of DORIS observations for Envisat orbits from 12 April 2002 till 2 January 2011.

Figure 6: RMS fits of SLR observations for TOPEX/Poseidon orbits from 23 September 1992 till 8 October 2005.

Figure 7: RMS fits of SLR observations for ERS-1 orbits from 1 August 1991 till 4 July 1996.

Figure 8: RMS fits of SXO observations for ERS-1 orbits from 1 August 1991 till 4 July 1996.

Figure 9: RMS fits of SLR observations for ERS-2 orbits from 13 May 1995 till 28 February 2006.

Figure 10: RMS fits of SXO observations for ERS-2 orbits from 13 May 1995 till 28 February 2006.

Figure 11: Reduction of the variance of atmosphere drag coefficients for Envisat VER5 orbit, as compared to the VER2 orbit.

Figure 12: Standard deviation sd of radial errors from the ERS-1, ERS-2 and Envisat missions per 10-day cycle. The six different orbit versions are plotted with different colors (red for VER2, green for VER3, blue for VER4, cyan for VER5, brown for VER6, and black for VER7).

Figure 13: Empirical auto-covariance functions of radial errors for three missions and six orbit versions (red for VER2, green for VER3, blue for VER4, cyan for VER5, brown for VER6, and black for VER7).

Figure 14: Relative center-of-origin shifts (y-component) w.r.t. the reference missions of three missions (ERS-1, ERS-2 and Envisat) using the three older orbit solutions (VER2 in red, VER3 in green, and VER4 in blue) (top plot) and their differences (bottom plot).

Figure 15: Relative center-of-origin shifts (y-component) w.r.t. reference missions of the ERS-1, ERS-2 and Envisat missions using orbits based on the EIGEN-6S2/A/B models (VER5 in cyan, VER6 in brown, and VER7 in black).

Figure 16: Geographically correlated errors for ERS-1 (left), ERS-2 (middle) and Envisat (right) based on the six different orbit solutions VER2 – VER7 (from top to bottom).

Figure 17: Global mean sea level from ERS-1 (blue, 1992 to 1996), ERS-2 (red), TOPEX (yellow/green), and Envisat (blue, 2002 to 2010) for the region $66^{\circ}\text{S}/\text{N}$ based on the six different orbit solutions (VER2 – VER7). A glacial isostatic adjustment (GIA) correction of 0.3 mm/year has been added. A 30-day boxcar filter has been applied for the TOPEX data. A few discontinuities for some curves are due to the unavailability of some altimeter corrections at the periods of question.

Figure 18: ERS-2 global mean sea level time series calculated for three orbit solutions; VER2 (red), VER3 (green) and VER4 (blue) from May 1995 (ERS-2 cycle 1) to July 2003 (ERS-2 cycle 85).

Figure 19: Map of the sea level trend [mm/year] derived from ERS-2 and Envisat data for the period May 1995 to October 2010 based on the VER6 orbit solution.

Figure 20: Map of the drift [mm/year] between the radial components of the VER4 and VER2 orbits for ERS-1 (October 1992 – June 1996), ERS-2 (May 1995 – June 2003), TOPEX (March 1993 – May 2004), and Envisat (October 2002 – December 2010).

Figure 21: Map of the drift [mm/year] between the radial components of the VER3 and VER2 orbits for ERS-1 (October 1992 – June 1996), ERS-2 (May 1995 – June 2003), TOPEX (March 1993 – May 2004), and Envisat (October 2002 – December 2010).

Figure 22: Map of the drift [mm/year] between the radial components of the VER6 and VER2 orbits for ERS-1 (October 1992 – June 1996), ERS-2 (May 1995 – June 2003), TOPEX (March 1993 – May 2004), and Envisat (October 2002 – December 2010).

Figure 23: Difference of the mean sea level calculated from ERS-2 and TOPEX for the period from June 1995 to June 1996 for the VER2 to VER7 orbit realizations. A bias of 7 cm has been applied to center the color axis.

Figure 24: Difference of the mean sea level calculated from Envisat and TOPEX for the period October 2002 to October 2003 for the VER2, VER3, VER4 orbit realizations. A bias of 45 cm has been applied to center the color axis.

Figure 25: Difference of the mean sea level calculated from Envisat and Jason-2 for 2010 for the VER2/GDR-C (CNES) and VER3/GDR-D (ESOC) orbit realizations. A bias of 41 cm has been applied to center the color axis.